

A MICROWAVE BEAM WAVEGUIDE UNDULATOR FOR A BRILLIANT ABOVE 100 KEV PHOTON SOURCE*

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Abstract

For generation of photons above 100 keV with a magnetic field strength in the range 0.2-0.5 Tesla, an undulator wavelength λ_u shorter than 5 mm may be needed with beam in the Advanced Photon Source (APS) storage ring. A microwave beam waveguide undulator system has been investigated for generation of such light. The waveguide structure consists of two parallel reflector surfaces that can be derived from an elliptically cylindrical waveguide. The structure can support deflecting TE_{m0} modes with very low microwave loss. A microwave ring resonator circuit employing the beam waveguide is considered to construct an undulator with the above requirement. Microwave properties of the beam waveguide structure have been investigated, and the design criteria for a microwave undulator are discussed.

1 INTRODUCTION

Undulators and wigglers that use microwave fields can have short undulator wavelength that is useful to generate high photon energy x-rays above 100 keV. A microwave undulator using a fundamental mode waveguide was reported in [1] and elsewhere. The fundamental mode waveguides can have certain limitations for a short undulator wavelength less than several millimeters due to narrow gap between metal walls and higher rf loss. The small aperture can be a problem for the beam passing through the undulator area; a microwave undulator with a physically large aperture is of interest. Using an overmoded quasi-optical beam waveguide can be useful to achieve the goal with low loss [2]. The microwave beam waveguide can support all TE and TM modes, but TE_{m0} modes (m =odd integer) are the useful modes for the undulator. With openings between the two reflectors, most unwanted modes may be damped completely. By constructing a ring resonator circuit with the beam waveguide, a microwave undulator can be possible with a reasonably low power microwave source.

Parameters of the electron beam in the Advanced Photon Source (APS) storage ring are shown in Table 1. The first harmonic synchrotron radiation spectra on beam axis ($\theta=0^\circ$) for various undulator fields are shown in Figure 1. The calculations were made in XOP [3][4] and show brilliance vs. photon energy around 100 keV with the undulator wavelength $\lambda_u=4.5$ mm at three undulator field strengths.

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Table 1: APS beam parameters

Beam Energy	7 GeV
Beam Current	100 mA
σ_x	0.342 mm
σ_y	0.091 mm
σ'_x	24 μ rad
σ'_y	9 μ rad

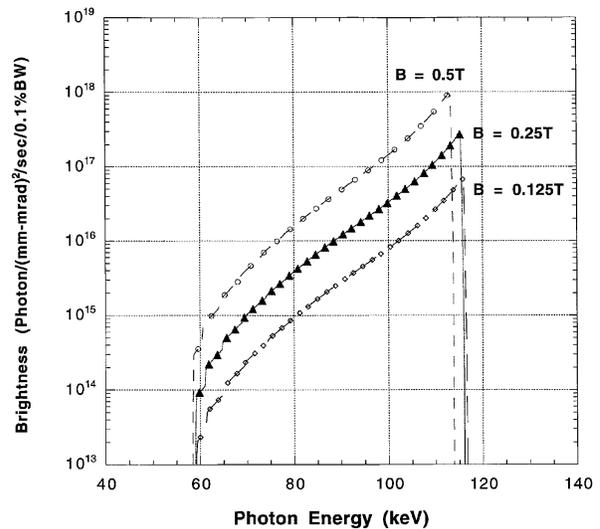


Figure 1: Brilliance vs. photon energy of first harmonic undulator radiation of the APS beam, $\lambda_u=4.5$ mm, $N=400$ periods, $L=1.8$ m.

2 BEAM WAVEGUIDE

A microwave beam waveguide and its TE_{m0} mode field distribution are shown in Figures 2(a) and 2(b). Two extruded concave reflectors are used with a gap between the two. The gap is important in order to provide damping of higher-order TE and TM modes and vacuum pumping for a practical undulator. The higher-order TE_{mn} and TM_{mn} modes ($n>0$) may not be supported by the open structure since the radiation loss through the openings can be significant.

The field strength needs to be uniform within a certain window area for coherent photon generation. The standing wave due to the transverse resonance has the transverse wavelength $\lambda_g^t > \lambda$. For a sinusoidal field variation, $\pm 9\%$ window gives 1% change from the peak field. The Gaussian microwave beam waist is given as

$$\omega_o(m) = \sqrt{\sqrt{2bd - d^2} / k_{m0}(m)} \quad (1)$$

where k_{m0} is the transverse wave number k_t for the TE_{m0} mode, b is the reflector focal length, and d is the distance between the two reflectors.

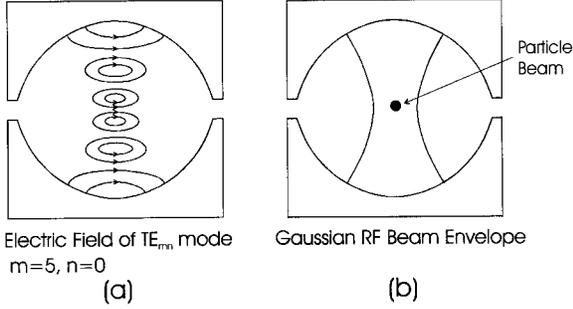


Figure 2: Cross section of a parallel reflector beam waveguide. (a) Electric field of the TE_{50} mode, (b) particle beam with respect to the microwave beam.

Beam waists at the waveguide center and on the reflector surfaces are shown in Figure 3. The waveguide system will have two distinct losses: one due to the metal surface resistance and the other due to spillover at the openings. The microwave beam waveguide can support TE modes with low loss due to its high Q factor; small diffraction and ohmic losses. The loss factors of diffraction loss and conductor loss of the beam waveguide are

$$\alpha_c \approx 2 \frac{R_s k_{m0}}{k_o h_{m0} d} \left(1 + \frac{h_{m0}^2}{2k_{m0}^2 d} \right) \quad (2)$$

$$\alpha_d = \frac{k_{m0}}{h_{m0}} \ln \left| \frac{1}{p} \right| \quad (3)$$

where $h_{m0}^2 = k^2 - k_{m0}^2$ and p is the reflected field intensity per reflection. Some properties and parameters of the beam waveguide are shown in [4].

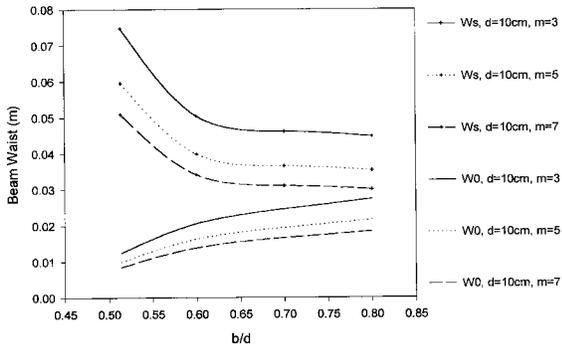


Figure 3: Beam waists of microwave in the beam waveguide. W_s and W_0 are waists on the reflector and at the center, respectively, $d=10$ cm, $\lambda_u=4.5$ mm.

The wave functions chosen in [5] are useful for estimating electromagnetic fields and parameters of the beam waveguide. The undulator field strength vs. b/d is

shown in Figure 4. The peak field strengths can be achieved at around $b/d \sim 0.6$ and was ~ 0.3 Tesla for 1 MW microwave input power in the $d=12$ cm case.

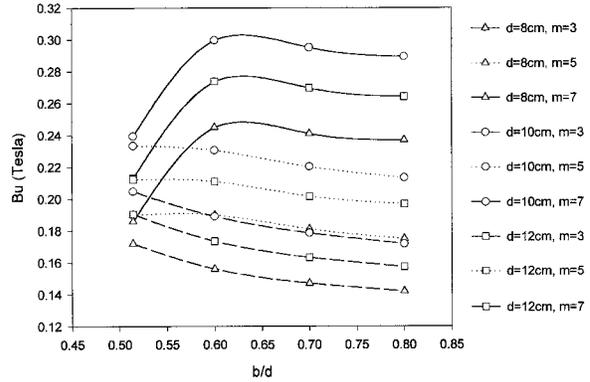


Figure 4: Undulator field strength in a beam waveguide. 1 MW microwave dissipation in 1 m, $\lambda_u=4.5$ mm.

3 PROPOSED DESIGN

A power amplification scheme known as ring resonator can be used to obtain the high field strength with low power microwave source [6]. The ring resonator consists of a closed microwave transmission line ring with a high directivity directional coupler. The beam waveguide can be used as the transmission line in the ring. The schematic diagram of the microwave ring resonator undulator is shown in Figure 5.

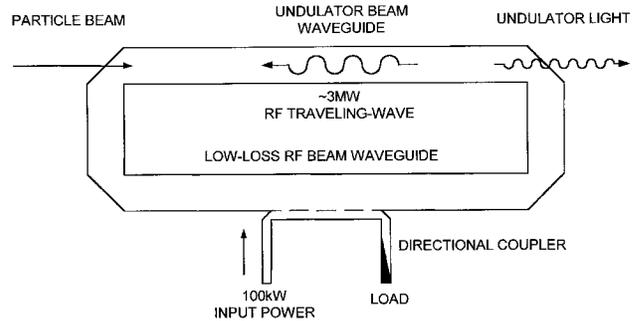


Figure 5. Schematic diagram of the microwave beam waveguide ring resonator undulator.

The ring can resonate at a frequency when the axial length is $N\lambda_g$, where λ_g is the guide wavelength. A ring resonator can provide amplified fields inside the resonator and have been used in certain high-power microwave experiments. The power gain of the system is given as [7] where c is the voltage coupling factor of the directional

$$G_p = \frac{c^2}{\{1 - 10^{-\alpha/20} (1 - c^2)\}^2} \quad (4)$$

coupler and α is the one-way attenuation around the ring measured in dB. The coupling of the directional coupler determines the power amplification factor. Due to its low microwave loss, a factor of 20-100 may be possible with practical high directivity couplers at above 30 GHz, so that a realistic system could be implemented.

The attenuation factor α is the limiting factor for the power gain of such structures as shown in Eq. (4). The diffraction loss dominates and thus limits the system performance. The directivity of the directional coupler must be made high enough so that the loss does not contribute much in total system loss. Estimated microwave properties of an example design of the 1.8-m resonator made of copper for $\lambda_u=4.5$ mm is shown in Table 2. The power gain of about 50 is obtained when the path loss is < 0.05 dB with a -15 -dB directional coupler. A regular waveguide to overmoded beam waveguide directional coupler can be constructed for this purpose. Note that the beam waveguide loss is much less than the loss in regular fundamental mode waveguides in the same frequency range of 0.5 - 1.0 dB/m. For the design $\lambda_g^1 \approx 20$ mm, a ± 1.8 -mm vertical window can give a field variation of $\pm 0.5\%$. The beam waist is ~ 20 mm; this translates to $\sim \pm 2$ mm horizontal window for $\pm 0.5\%$ field variation.

Table 2: An example of microwave ring resonator undulator parameters

Operating frequency (GHz)	34
Mode of operation	TE ₅₀
Reflector focal length, b (cm)	7.2
Reflector distance, d (cm)	12
Diffraction loss	0.014 dB/m
Reflector loss	0.0035 dB/m
Directional coupler coupling	-15 dB
Undulator field	0.25 T
Microwave source power	100 kW

A proposed design is shown in Figure 6. The design uses two halves of symmetrically machined plates. The entire ring resonator is made of beam waveguide to lower the microwave loss. The machined pieces are aligned with a gap between them to satisfy the mode damping and vacuum pumping as discussed above. A directional coupler is formed in the beam waveguide shown in the figure. Maintaining a resonance requires the use of tuners in the waveguide. Tuners can also be phase shifters in the form of electromagnetic, thermomechanical, or mechanical tuners. Temperature control of the waveguide structure can provide fine tuning of the resonance.

4 DISCUSSION

By using the low-loss, larger-aperture beam waveguide structure, a higher field can be obtained with sub-cm λ_u . The low-loss waveguide can help raise the power amplification factor over regular fundamental mode waveguides. The beam aperture in the microwave

standing wave field does not have uniform strength like in DC magnet systems, but still can be useful in generating a synchrotron light. In the example design, the power loss is < 0.02 dB/m so the axial field uniformity in a 1.8-m structure will be better than 0.1%. If more precise field uniformity is desired, the reflecting surfaces can be tailored to match the wavelength and the field strength. By increasing the microwave frequency, photon energy much higher than 100 keV can be generated. Recently, klystron and gyrotron amplifiers have become commercially available in the above frequency range for > 200 kW pulses and for 50-100 kW CW, which is considered sufficient for this application.

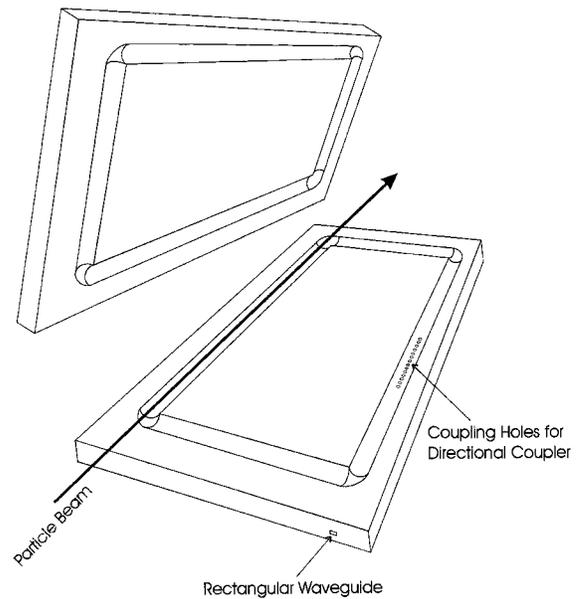


Figure 6: A proposed design of a beam waveguide microwave undulator.

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